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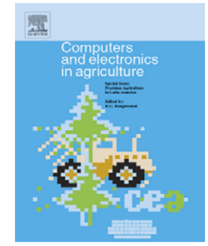

Agricultural applications of a low-cost infrared thermometer

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ABSTRACT

Plant canopy temperature is used in many studies of plant/environment interactions and non-contact measurement is often made with radiometric surface thermometers commonly referred to as infrared thermometers. Industrial-quality infrared thermocouples are widely available and often used in agricultural research. While research on canopy temperature has provided management tools for production agriculture, the high cost of the industrial-quality infrared thermocouples has limited their adoption and use in production agriculture settings. Our objective was to evaluate a low-cost consumer-quality infrared thermocouple as a component of a wireless thermal monitoring system designed for use in a production agriculture setting. The performances of industrial-quality and low-cost consumer-quality sensors were compared under controlled constant temperature and under field conditions using both grass and cotton canopies. Results demonstrate that under controlled constant-temperature the two types of infrared thermocouples were "significantly the same" at 10 °C, 20 °C and 30 °C and "significantly not the same" at 40 °C and 50 °C. Across the temperature range tested, the consumer-quality infrared thermocouples temperature reading was closer to the thermocouple reading than the industrial-quality infrared thermocouples. A field comparison of industrial-quality and consumer-quality infrared thermocouple sensors monitoring a grass canopy and a cotton canopy indicated that the two types of sensors were similar over a 13–35 °C range. The measurement of temperature made with two types of sensors would not differ significantly. Based on these results we conclude that the lower-cost consumer-quality infrared thermometers are suitable for use in production agricultural applications.

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1. Introduction

Temperature affects virtually all aspects of plant growth and development through a variety of mechanisms. In agricultural systems, temperature in the field is dynamic on both diurnal and seasonal scales. Air temperature is often used as a surrogate for plant temperature though there are some situations under which the difference between air and plant temperature is important and both must be measured. While air temperature is relatively straightforward to measure with thermometers, thermocouples and/or thermistors, the measurement of plant temperature is generally more difficult to accomplish, particularly if continuous non-destructive measurements are necessary. The value of measurements of plant canopy temperature in agriculture was established in the early 1980s (Idso, 1982; Jackson, 1982).

Non-contact measurement of leaf temperature is often accomplished through the use of radiometric surface thermometers commonly referred to as infrared thermometers (IRTs). The advantages of infrared thermometry in studies of

Abbreviations: IRTs, infrared thermometers; IRt/c, infrared thermocouple; C-Q IRT, consumer-quality IRTs; I-Q IRT, industrial-quality IRTs; TOST, two one-sided *t*-tests.

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plant temperature include: no need for physical contact with the plant, simple automation of data collection and non-point measurements that accommodate inherent spatial variability.

The cost and complexity of infrared thermometers have changed significantly over the approximately 30 years that they have been used in agricultural settings. The IRTs commonly used in earlier agricultural studies had mechanical components, required external power sources and cost in excess of $3000 (USD). Failure rates of the instruments were such that it was not uncommon to have 50% of deployed instruments fail within a single growing season (James Mahan, personal observation).

The IRTs initially used in agricultural studies, while adequate for research, were not particularly suitable for use in production agriculture settings. The development of the infrared thermocouple often referred to as an IRt/c has resulted in increased simplicity and affordability of instruments for temperature measurements. A wide variety of industrial-quality IRt/c's are commercially available from a number of manufacturers and in recent years the agricultural use of such IRT devices has increased. The IRTs have been used to monitor plant canopy temperatures in a large number of studies involving detection of plant water stress (Jackson et al., 1981; Hatfield, 1990; Wanjura and Mahan, 1994; Pinter et al., 2003; Peters and Evett, 2004). This work with industrial-quality IRT devices demonstrates their suitability for use in agricultural environments, however their cost, coupled with the complexity and the additional cost of thermocouple wiring in field environments, led us to consider alternative sensors that would be more suitable to use in production agriculture environments.

Currently relatively inexpensive IRT sensors are commercially available. Such devices, though often accompanied by detailed "specification sheets" are generally considered inferior to the industrial-quality devices that are available at 10 times the cost. In this paper these low-cost sensors are referred to as consumer-quality IRTs (C-Q IRT) and the costlier devices as industrial-quality IRTs (I-Q IRT).

Based on our experience and that of others (Wang et al., 2006), the desirable characteristics of an IRt/c-based temperature monitoring system suitable for use in production agricultural settings are: (1) affordability (ideally to the point of disposability), (2) wireless data transfer, and (3) simple in-field serviceability. In this paper we report and evaluate the use of a low-cost consumer-quality IRT as a component of a wireless thermal monitoring system designed for use in production agriculture. It is not the goal of this paper to debate the merits and demerits of various types of IRTs as temperature measuring devices but rather to define, if one indeed exists, the range of environmental conditions over which a consumer-quality IRT can be used in place of an industrial-quality sensor. Given that the goal is to evaluate a potential replacement for the industrial-quality IRT sensors, these sensors represent the de facto performance standard in this study.

The question addressed in this study is: "Can a relatively low-cost consumer-quality IRT effectively replace a higher-cost industrial-quality IRT for use in an agricultural production setting?" Our hypothesis that, within the range of temperatures relevant for agricultural applications, temperatures measured with a low-cost consumer-quality IRT is functionally indistinguishable from those measured with an industrial-quality IRT sensor commonly used for agricultural research.

Table 1 – Manufacturer's specifications for industrial-quality and consumer-quality infrared thermometer (IRT) sensors

Parameter	Industrial-quality (I-Q) IRT	Consumer-quality (C-Q) IRT
Operating range	−18 to 100 °C	−10 to 50 °C
Measurement range	0–50 °C	−33 to 220 °C
Minimum spot size	8 mm	25 mm
Field of view (distance vs. scene)	2 to 1	1 to 1
Linear range (2%)	0–50 °C	

The objectives of the study were: (1) to compare thermal measurements between two types of IRT devices and (2) to determine reliability of these sensors in a field setting over a growing season. The experimental approach involved comparisons of the two types of sensors to a fine wire thermocouple under controlled constant temperatures and comparisons of the two sensors under field conditions over the course of several days using both grass and cotton canopies. For measurements at a variety of constant temperatures, the target temperatures were varied and the sensor temperatures were maintained constant at 25 °C. Measurements in the field were carried out within a continuously variable thermal environment with both sensor temperature and target temperatures changing over the measurement interval.

2. Materials and methods

2.1. *Temperature measurement devices*

Temperatures were measured with thermocouples and two types of IRt/c devices. The thermocouples were type K with a bead size of 1 mm. The industrial-quality IRT was an Exergen model IRt/c.2 type K 27C (Exergen, Watertown, MA) that is recommended by the manufacturer for agricultural applications. The consumer-quality sensor was a Zytemp model TN901 infrared thermometer (Zytemp HsinChu, Taiwan, ROC). This particular sensor is not, by all indications, an industrial-quality instrument. The advantages are its low cost (1/10th that of an industrial-quality IRT) and "plug and play" configuration that allows for simple in-field service/replacement. The operational characteristics for the two types of devices, as reported by the manufacturers, are summarized in Table 1.

The I-Q IRT was connected to a Campbell Scientific CR1000 data logger for recording temperatures. The data collection interval was 5 s for constant temperature measurements and 15 min for field measurements.

The C-Q IRT sensor was incorporated into a wireless thermometry system designed and constructed by the USDA-ARS and Accent Engineering (Lubbock, TX). The system consists of a remote and a base unit. The remote unit consists of a C-Q IRT sensor mounted in a circuit board that serves to record the output of the C-Q IRT. Measured temperature values were collected by the remote in anticipation of transmission to the base unit. For testing, the remote unit was set to transmit a temperature value once every 5 s. The temperature transmission was received by the base unit, which stores it in memory for retrieval. Under field conditions the remote unit monitors temperature every 15 s and transmits temperature to the base unit on a 15-min interval. Both collection and transmission time intervals are user-defined.

2.2. *Comparisons to known temperature standards*

Performance of both IRT sensors was determined at fixed temperatures set by thermal controller that uses thermoelectric units to output specified temperatures in a series of target blocks (7.5 cm × 5 cm). The surface of the thermal blocks was covered with copper plates maintained at a specified temperature through the thermoelectric controller. The temperature of the thermal block during each measuring period was monitored with a fine-wire thermocouple (type K) attached to an Omega Model HH21 microprocessor thermometer (Omega Engineering INC, Stamford, CT). The temperature of the thermal blocks was adjusted through a 10–50 °C thermal range in 10 °C increments. For each reading both IRTs were fixed at 2.5 cm above and perpendicular to the thermal plate. Five measurements were made and recorded at 5-s intervals for each IRT/thermocouple temperature setting. Six IRTs of each type were used to make five temperature readings at each temperature setting.

2.3. *Monitoring temperatures of plant canopies in the field*

Under field conditions the plant canopy temperature was constantly variable and it is virtually impossible to replicate measurements of a specific canopy position. Thus several measurements of canopies that were both temporally and spatially similar were made by several instruments of each IRT type over a period of several days.

The temperature of grass and cotton canopies was measured with both I-Q and C-Q IRT sensors in Lubbock, TX during the early and late summer of 2007. These sensors were mounted ~10 cm above the plant canopy resulting in a spot size of ~5 cm and ~10 cm diameter for the I-Q and C-Q sensors. The plant canopy completely filled the field of view of the devices. The canopy temperature was measured on a 5-s interval with the average canopy temperature recorded every 15 min. Temperature was recorded at 1-min intervals and reported as 15-min averages. Five I-Q and six C-Q IRT sensors were positioned above a uniform canopy of a bermuda grass lawn during 1–4 June 2007. Later in the season, from 25 to 29 September 2007, two I-Q and four C-Q IRT sensors were positioned over a mature cotton canopy.

2.4. *Data analysis*

To compare the temperatures measured by both I-Q and C-Q IRT sensors across a 10–50 °C temperature range, equivalence statistical testing procedures were used to calculate differences in measured mean temperature values. A threshold difference of 0.5 °C was selected for which smaller difference equated to practical equivalence, i.e. the same temperature. Data was fitted by this method using JMP v. 7, which constructs the testing using two one-sided *t*-tests (TOST) from both sides of the difference interval. If both tests rejected the null hypothesis, the groups were considered equivalent or from a statistical view to be “significantly the same”.

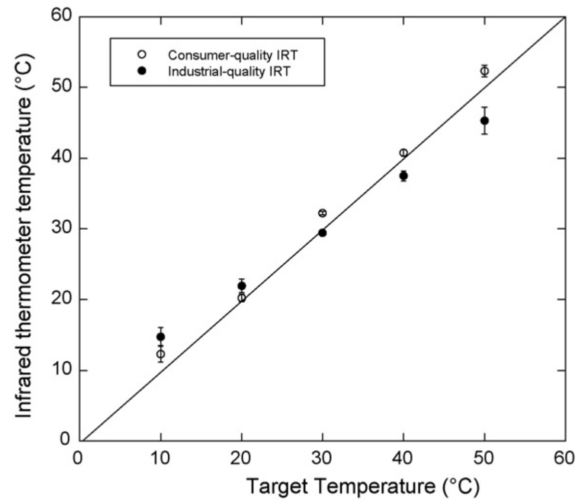

Fig. 1 – Measurement of constant temperatures by industrial-quality IRT and consumer-quality IRT sensors. Six devices of each type were positioned 2.5 cm above a constant temperature target. The temperature of the target surface was measured with a thermocouple. Both types of IRTs were measured at 5-s intervals for a total of five measurements per individual device.

3. Results

Fig. 1 shows the comparisons of average thermocouple-measured temperatures with those measured by I-Q and C-Q IRT sensors across 10–50 °C in 10 °C increments. These results indicated that the two types of IRTs differ in terms of accurately measuring the temperature of a constant-temperature metal target plate. The results showed that their equivalence depends on the measured target temperature. The two types of IRTs were “significantly the same” at 10 °C, 20 °C and 30 °C and were “significantly not the same” at 40 °C and 50 °C. Across the entire temperature range, the C-Q IRT temperature reading was closer to the thermocouple reading when compared to the I-Q IRT.

A comparison in the ability of the two types of IRTs to measure plant canopy temperatures is more complex than those involving the measurement of a constant temperature target. Two factors contribute to this complexity. Firstly, the canopy temperature is dynamic and thus changes over time in the field. Secondly, as a result of the continuous variation in canopy temperature, it is virtually impossible to measure the temperature of a single canopy target with multiple devices at the same moment in time. In light of this variation, field measurements can provide insight into the variation among a group of devices monitoring the temperature of a population of plant canopies (scenes if you will) but are not particularly effective at detecting differences between or among devices of different types measuring an identical temperature. In light of

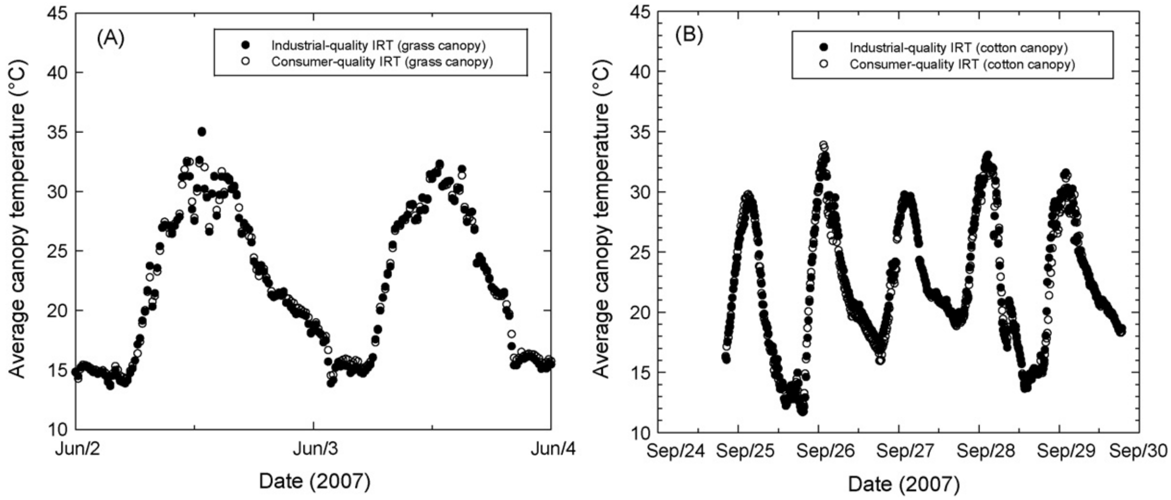

Fig. 2 – Temperature of grass (A) and cotton (B) canopies measured with industrial-quality IRT and consumer-quality IRT sensors during the early and late summer of 2007 in Lubbock, TX. Grass canopy temperature was measured from 1 to 4 June 2007 in Lubbock, TX. Five devices of each type were positioned 10 cm above the canopy at a viewing angle of 30°. The temperature of the canopy was measured on 5-s intervals with the average canopy temperature recorded every 15 min. Cotton canopy measured with industrial-quality and consumer-quality IRT sensors from 25 to 29 September 2007 in Lubbock, TX. The two industrial-quality and four consumer-quality IRT sensors were positioned 10 cm above the canopy at a viewing angle of 30°. The temperature of the canopy was measured on 5-s intervals with the average canopy temperature recorded every 15 min.

these restrictions, the field performance of the two types of IRT sensors was assessed by comparing the results of the monitoring of canopy temperature over the course of several days with several devices of each IRT type. Fig. 2A shows the results of measuring the temperature of a grass canopy with the I-Q and C-Q IRT sensors from 1 to 4 June 2007. Fig. 2B shows the results of measuring the temperature of a cotton canopy by I-Q and C-Q IRT sensors from 25 to 29 September 2007.

The results of the in-field canopy temperature measurements (Fig. 2A and B) are representative and typical of those obtained for many days in our laboratory. Both types of sensors were responsive to the diurnal variation in canopy temperature and capable of measuring canopy temperatures in the field. With respect to canopy temperature measurement in the field, the inherent difficultly in obtaining replicated measurements of a single canopy target suggests that, in this study, the most relevant comparison is between the performance of a collection of I-Q IRT sensors and a collection of the C-Q IRT sensors in a field environment. Fig. 3A shows a comparison of the 15-min means from I-Q and C-Q IRT sensors monitoring

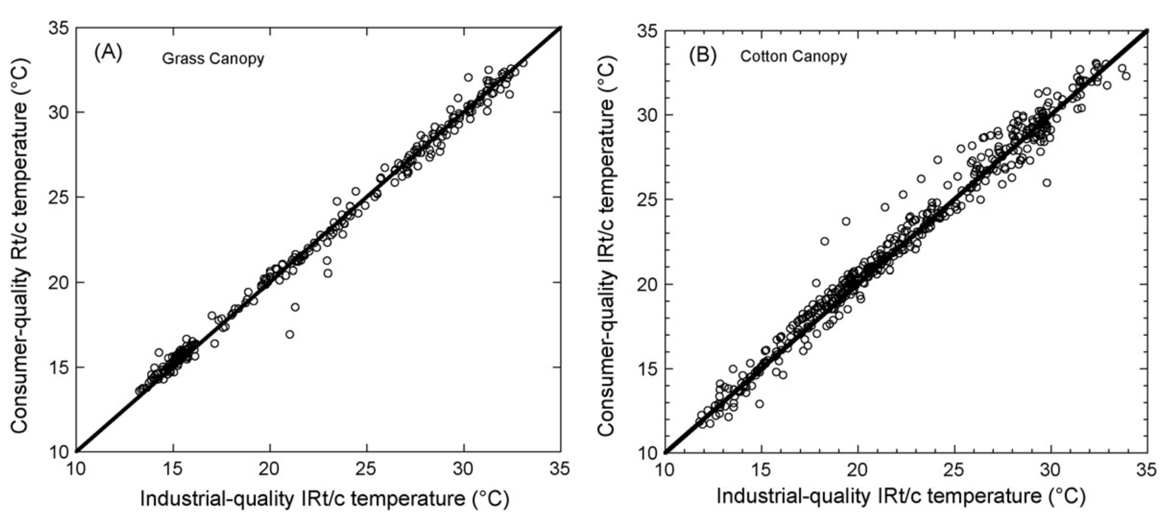

Fig. 3 – Comparison of the 15-min means of industrial-quality IRT and consumer-quality IRT sensors monitoring canopy temperatures of grass (A) and cotton (B) canopies in Lubbock, TX during the summer of 2007. Five devices of each type monitored the canopy temperature of a grass canopy from 1 to 4 June 2007 in Lubbock, TX. Two industrial-quality and four consumer-quality IRT devices monitored the canopy temperature of a cotton canopy from 25 to 29 September 2007 in Lubbock, TX.

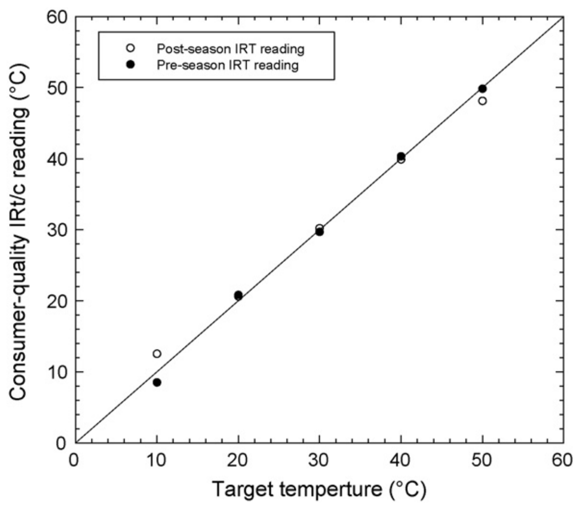

Fig. 4 – Comparison of the temperature measurement of the consumer-quality IRT sensors at the end of the field deployment with the consumer-quality IRT data collected prior to deployment. Thermal response of the consumer-quality IRT was measured using constant temperature targets prior to field deployment (April 2007) and following a 5-month deployment in the field (September 2007).

a grass canopy and Fig. 3B shows the results obtained from a similar installation over a cotton canopy. These results suggest that the values of temperature obtained with these two types of sensors were similar over a 13–35 °C range.

The IRT sensors were initially placed in the field in May and were removed from service at the end of September. Thereafter, their performance was reassessed using the constant temperature target system previously described. Fig. 4 shows the comparison of the post- and pre-season temperature measurements of the two types of sensors.

4. Discussion

The question addressed in this study was "Can a low-cost C-Q IRT sensor effectively replace a higher-cost I-Q IRT sensor for use in an agricultural production setting?" Obviously the answer to this question depends on what is meant by "effectively replace" and our selection of an appropriate IRT sensor is based on lengthy experience with I-Q IRTs in agricultural research.

During the last 15 years personnel in our laboratory have deployed more than 100 I-Q IRT sensors to monitor plant temperatures under growth chamber, greenhouse and field conditions. Our experience in the use of these sensors in field environments is extensive and the results described in numerous papers (Wanjura et al., 1992, 1995, 2006; Wanjura and Mahan, 1994). The I-Q IRT sensors have proven to be adequate for the day-to-day monitoring of plant temperatures in agricultural field settings and are particularly well-suited for use as a component of the BIOTIC irrigation scheduling protocol (Upchurch et al., 1996; Mahan et al., 2005). Based on our experience in research and production settings, the need for a low-cost IRT sensor that could be used in production agriculture became evident. However, it was clear that a high-cost IRT sensor would not be adopted and used and that a less expensive alternative was necessary. Furthermore, the lower-cost IRT might require some compromises in terms of durability and data quality in comparison with our existing instrument systems. Such is the transition from a research to a production agriculture application. The intent was to identify, if possible, the point where the negative aspects of the proposed substitute outweighed their positives.

Equivalent and adequate are the two terms to assess using low-cost C-Q IRTs, in place of the higher-cost I-Q IRT sensors, which were evaluated in this study. Equivalence, a quantitative statistical term, suggests the possibility of a one-for-one replacement while adequacy, a purely qualitative term, would require a more defined set of conditions and uses for which the devices could be interchanged. The functional specification of equivalence is summarized in the following question. If presented with a series of measurements made by a collection of I-Q IRTs and C-Q IRTs, could an observer, with a defined degree of confidence, determine which measurements were made by which type of device?

In terms of the use in an irrigation scheduling device based on the BIOTIC protocol (Upchurch et al., 1996), which requires only a determination of canopy temperature as being above or below a temperature threshold, the low-cost C-Q IRT are effectively equivalent to the I-Q sensors. In our experience the temperature thresholds that are involved in BIOTIC irrigation of crops in temperate environments range from a low of 22 °C for potato to a high of 30 °C for corn. Within this temperature range both the I-Q and C-Q IRT are equally capable of detecting canopy temperatures in excess of a specified temperature threshold.

In an application in which the IRT sensors are used to monitor temperatures over a wider environmental range that might be encountered over a growing season, both types of IRT devices are quite similar in performance. Performance in the range from 10 °C to 50 °C, which encapsulates the range of temperatures experienced by plants in temperate climatic regions, the two types of IRT sensors would not differ significantly. It is notable that we have not included information in the performance of either type of sensor at temperatures below 10 °C or above 50 °C. These temperatures while certainly detrimental to plants are not within the range experienced by crops in most temperate regions.

5. Conclusions

Results indicated that the values of temperature obtained with the I-Q and C-Q IRT sensors are not strictly equivalent. For example, in a given set of temperature measurements, the readings can with some certainty be associated to one type of sensor or the other. In fact, the results indicated that the temperature measurements of the C-Q IRT sensors more closely agree with those obtained with a fine-wire thermocouple measuring the temperature of a target maintained at a constant temperature. The I-Q IRT sensors used in the study have a cost of ~$300 USD and the C-Q IRT sensors used were purchased for ~$30 USD. Not only are the C-Q IRT devices less costly relative to the I-Q IRT devices, but in absolute terms they are inexpensive enough to be considered a “disposable” component of a measuring system. In our experience they are too inexpensive to even attempt repairs and these sensors, when necessary, can be replaced in the field in 5 min with only a screw driver. When incorporated into a simple wireless system, the devices were capable of providing in-field temperature monitoring for a 3-month period with a set of four alkaline AAA batteries.

Overall we were satisfied with the results obtained from side-by-side comparisons of temperatures obtained with the C-Q and I-Q IRT sensors over the course of the 2007 growing season. During this field-testing period, of the more than 20 C-Q IRT sensors deployed in the field, only one device failed. A result of sprinkler-induced water incursion.

In the final analysis the usefulness of any sensor is determined by a number of factors including; its relative cost, ease of use, and its accuracy and precision. In any application these factors interact and define an “envelope” of conditions in which the use of the sensor is appropriate and for which it is ill suited. Thermal environments in agricultural settings are dynamic but vary within relatively small temperature scales. The annual range in temperate climates of ambient temperature within an agricultural setting may vary from subzero lows to highs in excess of 40 °C. The range of plant temperatures during a growing season is generally narrower. For example, cotton canopy temperatures in the southern High Plains region of Texas during the growing season can typically range from a minimum of 5 °C to a maximum of 40 °C (under water deficit conditions).

In light of the previous analysis, what would be the basis for changing from one type of IRT sensor to another. Clearly the issue of cost becomes the strongest argument though cost itself may not be a sufficient basis. It is not the prospect of reducing the cost of an implementation of plant canopy temperature measurements but rather the ability, for the same cost, to include a larger number of sensors in the analysis and increase the sampling density.

In closing, it is appropriate to recognize that, at least for some practitioners of plant temperature analysis, even the I-Q IRT sensors used as the standard for comparisons in this study are not considered sufficiently accurate and/or precise for use in some agricultural applications. In applications for which temperature must be precisely and accurately known, the currently available higher-quality I-Q IRTs (e.g. Apogee Instrument Inc., Logan, UT) are most properly the instrument of choice. If, on the other hand, the deployment of a large number of lower-cost sensors would allow a more complete analysis of the spatial and temporal variation of temperature, and thus the inclusion of a larger number of lower-cost devices might be advantageous and appropriate.

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